TECHNICAL REPORT

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INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

Abstract

Efforts continue under this contract to develop algorithms for the computation of sea surface temperature (SST) from MODIS infrared retrievals. This effort includes radiative transfer modeling, comparison of *in situ* and satellite observations, development and evaluation of processing and networking methodologies for algorithm computation and data accession, evaluation of surface validation approaches for IR radiances, development of experimental instrumentation, and participation in MODIS (project) related activities. Activities in this contract period have focused on radiative transfer modeling, evaluation of atmospheric correction methodologies, analysis of field data, objective analysis approaches, revision of the ATBD and participation in the ATBD review process, and participation in MODIS meetings.

MODIS INFRARED ALGORITHM DEVELOPMENT

A. Near Term Objectives

A.1. Continue algorithmic development efforts based on experimental match-up databases and radiative transfer models.

A.2. Continue interaction with the MODIS Instrument Team through meetings and electronic communications, and provide support for MCST pre-launch calibration activities.

A.3 Continue evaluation of different approaches for global SST data assimilation and work on statistically based objective analysis approaches.

A.4 Continue evaluation of high-speed network interconnection technologies.

A.5 Continue development of *in situ* validation approaches for the MODIS IR bands.

A.6 Provide investigator and staff support for the preceding items.

B. Overview of Current Progress

B.1 January-June 1997

Activities during the past six months have continued on the previously initiated tasks. There have been specific continuing efforts in the areas of (a) radiative transfer modeling, (b) generation of model based retrieval algorithms, (c) continued work on IR calibration/validation as part of the MODIS Ocean Science Team cruise effort, (d) analysis of consequences of imperfect pre-launch characterization of the MODIS infrared channels, and (e) test and evaluation of an experimental wide area network based on ATM technology. In addition, previously initiated activities such as team related activities continue.

Special foci during this six month period have been:

1) AVHRR *in situ* comparison data base studies.
2) Continue analysis of measurements from the DOE/NOAA/NASA ARM Combined Sensor Project cruise in the Tropical Western Pacific in the spring of 1996.
3) Construction of a marine FTIR instrumentation for cal/val applications by UW/SSEC via subcontract .
4) Negotiate for ship-time for post-launch validation, and explore options for long-term validation from fixed platforms.

B.1.1 Radiative Transfer Modeling

Dr. Richard Sikorski has been modeling sea-surface and atmospheric emitted and reflected infrared radiation, for the purpose of simulation of the brightness temperatures (BTs) measured by satellite instruments with various spectral sensitivities, for various atmospheric and marine conditions.

New characterizations of the MODIS thermal IR detectors have required analyses of variations in the relative spectral responses (RSRs) versus the MODIS thermal IR error budget. The impact depends greatly on the total vapor and the vertical vapor structure of the simulated atmospheres. The radiative transfer model and the radiosonde database have been redesigned to meet these analytical needs. The radiosonde database of vapor/temperature profiles is now being processed into an indexed database of atmospheric optical properties. A broader range of atmospheres are being added to the database. The spectral range of the model has been extended beyond the original NOAA-9 and NOAA-11 channels to cover the full range of MODIS IR bands. The model now accepts alternate sets of RSRs and allows additional loadable spectral modifiers for instrument errors, *e.g.* mirror reflectivity, mirror emissivity, and band cross-talk. This has been used to study the potential impact of channel-to-channel center-wavelength shifts that SBRS recently measured in the thermal IR bands.

B.1.2 Algorithm Development Efforts Based on Experimental Match-up Data bases

Focus during this period has been on evaluation of unbiased approaches for parameter estimation. It has been determined that improper attention to cross-correlation effects on multiple regression approaches is a significant issue when dealing with *in situ* sea surface temperature (SST) datasets. Dr. A. Mariano has developed an approach which removes such correlation and improves the quality of the regressed coefficients. Computer runs are in process to validate the approach and determine the stability of the derived atmospheric correction equations.

B.1.3 The Combined Sensor Cruise of the NOAA ship *Discoverer*

As described in earlier reports, the Combined Sensor Cruise in the Tropical Western Pacific in March–April 1996, generated an unprecedented array of measurements of atmospheric boundary layer and sea surface temperature. The radiometric and *in-situ* measurements of sea–surface temperature taken by the University of Miami and University of Wisconsin group continue to be analyzed, but this is currently being delayed awaiting the release of air–sea flux measurements taken by other cruise participants.

A publication describing the cruise and the initial scientific results has been submitted to the *Bulletin of the American Meterological Society*, and posters describing the measurements of the skin sea–surface temperature were presented at the AMS Conference on Atmospheric Radiation and at the 7th Atmospheric Radiation Measurements Program Science Team Meeting.

B.1.4 Future validation campaign (at sea cruise) planning

R/V Revelle Cruise

Preparations are underway to participate in the cruise of the *R/V Revelle*, leaving Honolulu on September 28 and arriving in Lyttleton, New Zealand, October 14. This cruise will cover a wide range of climate regimes (21.5°N to 43.5°S) over a distance of ~7,900 km. It is planned that M–AERI measurements will be made on a continuous basis while the ship is underway, together with all of the supporting environmental measurements. It will be an excellent test of the planned MODIS SST validation strategy, and the M–AERI measurements will be compared to data from the AVHRR (NOAA satellites), SVISSR (GMS), and ATSR-2 (ERS-2) spacecraft radiometers.

CCGC *Louis S. St. Laurent*

The Canadian research agency NSERC has funded the scientific voyages of the Canadian icebreaking research vessel *Louis S. St. Laurent* to the north of Baffin Bay (see report for July-December 1996). Dr. Minnett attended a meeting of the scientists involved in this program in Quebec City, and the offer of berths during one or several of the cruises in 1998 was confirmed. Although these cruises will take place before the EOS-AM launch, they will provide an extremely valuable opportunity to test the deployment of the M-AERI and ancillary equipment in a polar environment.

USCGC *Polar Sea* and PFS *Polarstern*

Discussions have continued with the US Coast Guard on the potential use of the *USCGC Polar Sea* on its annual supply voyages from Seattle to Antarctica and return. The prospects of this appear to be very good, but a firm agreement is not yet in hand. Similarly, unofficial approval has been granted of a request to mount the M-AERI on the German ice-breaking research vessel *Polarstern* on a voyage from Germany to Antarctica. Demand for berths is likely to limit the M-AERI deployment to the transit from Germany to Cape Town as the ship is likely to be fully subscribed for the leg from South Africa to Antarctica. The dates tentatively offered are mid-December 1999 to early January 2000.

B.1.5 Meetings at RSMAS

RSMAS hosted two meetings in January 1997: the Thermal Infrared Task Group chaired by Dr. P. Minnett and the MODIS Oceans Group chaired by Dr. W. Esaias of GSFC.

The Thermal Infrared Task Group heard from the MCST about the pre-launch characterization of the thermal infrared channels and discussed the major concerns. These include cross-talk between channels, uncertainties in the spectral response functions of the channels, uncertainties in the specification of the spectral and angular properties of the reflectivity/emissivity of the scan mirror, digitizer non-linearities, etc. A full report was submitted to Dr. V. V. Salomonson soon after the group met.

Another concern of the Task Group is that the construction schedule of the FM-1 instrument is so far advanced that the lessons learned from the PFM tests are not being incorporated into the FM-1, and some of the short-comings are being propagated forward.

The group also discussed post-launch validation efforts and the prospects of coordinating these with the activities of other instrument teams. Dr. Minnett contacted the ASTER and MISR groups. The ASTER team are eager to coordinate validation activities.

B.1.6 M-AERI

The first Marine Atmosphere Emitted Radiance Interferometer (M-AERI) was delivered to RSMAS in early April. This has been developed and constructed at the Space Science and Engineering Center at the University of Wisconsin–Madison under contract, and will be the primary instrument for the validation of skin sea–surface temperatures measured by MODIS.

The M–AERI is a Fourier Transform Interferometer operating in the infrared wavelength range of ~3µm to ~18µm, and includes two black body calibration targets to provide absolute radiometric calibration. Calibration of these targets are traceable to NIST standards. The measured spectra have a spectral resolution of ~0.5cm^{-1} and observed skin temperatures are accurate to ~0.1K. The instrument has been described in earlier project reports.

The M–AERI/01 contains several design improvements that have resulted from the two earlier cruises using proto-type instruments (*RV Pelican* in January 1995; NOAA *S Discoverer* in March-April 1996 - see earlier reports), and these include:

a) Improved weatherproofing of the external unit.
b) Better protection for the scan mirror against contamination by spray or rain. The scan mirror

is now enclosed in a cylinder with a small viewing aperture. When a rain detector, mounted close to the mirror, registers spray or rain, the measurement sequence is interrupted and the mirror rotates to the position where it views one of the internal black body targets. The aperture in the cylinder is then enclosed by the mouth of the black body cavity. After no rainfall or spray is detected for a given time interval, the sampling sequence is resumed.

c) Integral GPS receiver to provide geographical positions and a time base to update the computer clock.
d) Integral pitch-roll sensors to monitor the ship's motion.
e) Modular electronics.
f) Use of a single computer to control the instrument as well as log and display the data.
g) Longer cables between the external unit and the control/logging computer.
h) Mounting the computer and control electronics in shock-absorbing racks which are also transport containers.

M–AERI/01 was mounted on the *R/V Calanus* as part of the initial acceptance tests and a test cruise was conducted in Biscayne Bay close to RSMAS on April 9. M–AERI/01 operated without problems and no interference was detected from the ship's radios or radars. The derived skin temperatures were compared against *in-situ* measurements from a thermistor on a towed float and the agreement is very good (Figure 1), the discrepancy being due to the surface skin effect.

M–AERI/01 is now set up in a laboratory and has operated without problem since April 10. The Stirling Cycle cooler can achieve and sustain the detectors at liquid nitrogen temperatures(~78K). An instrument platform and 15m instrument tower will soon be installed on the roof of the three-story Marine Sciences Center at RSMAS. The M–AERI will be mounted there to have a clear view of the water in Biscayne Bay and of the sky from horizon to zenith. Other ancillary instruments will also be installed there. An infrared radiometry laboratory will be set up in the Marine Sciences Center, with funding from School and Divisional budgets.

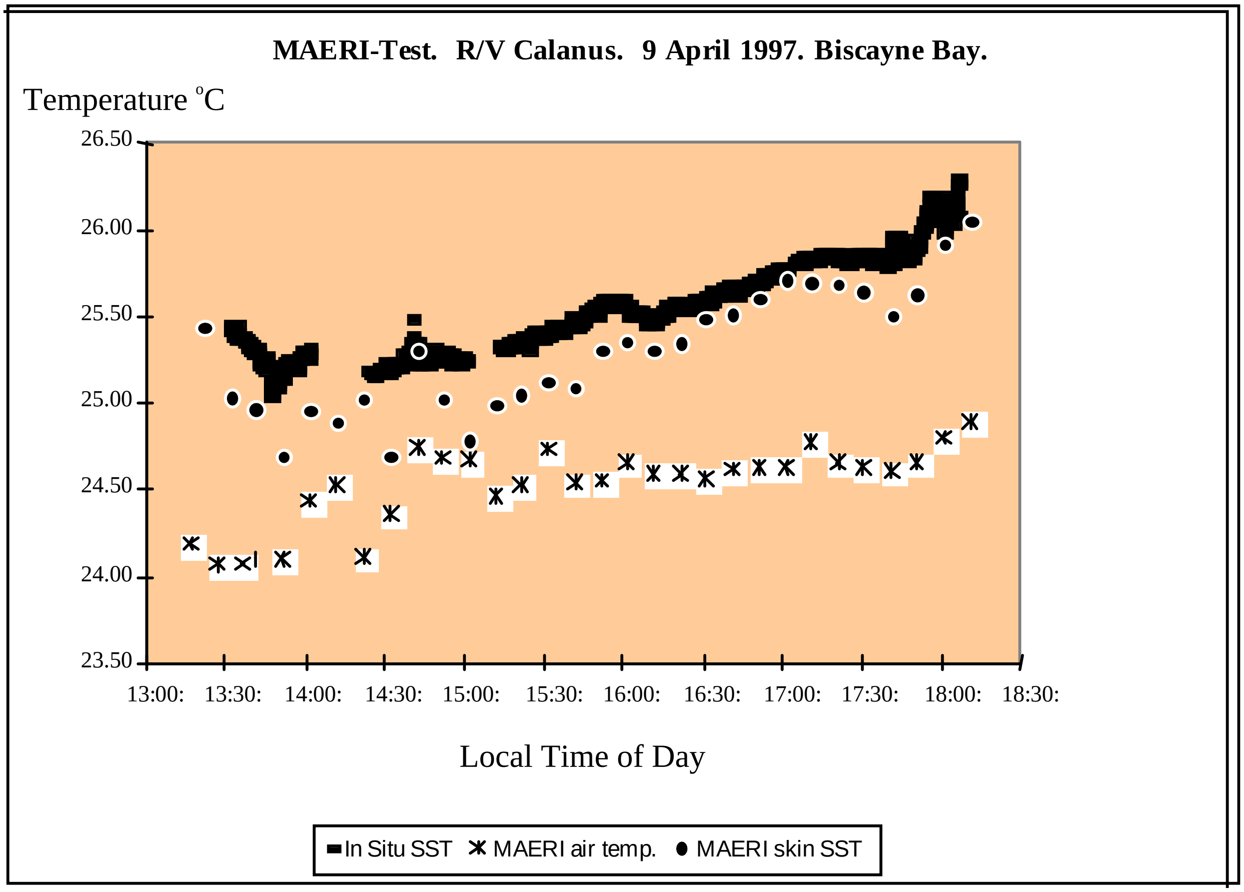


Figure 1. Time series of measurements taken from the R/V *Calanus* during the acceptance test of M-AERI/01. The derived skin SST measurements from M-AERI/01 are consistently cooler than the *in situ* temperatures measured from a towed float at a depth of <0.1m. M-AERI air temperatures, derived from close-to-horizontal measurements in less transparent parts of the infrared spectra, are cooler still. This follows physical expectations.

Several other University groups have expressed interest in collaborating with the RSMAS group and making use of these new facilities. They have applied for funding under the NRA-97-03, "Satellite Remote Sensing Measurement Accuracy, Variability and Validation Studies."

M-AERI/02 and M-AERI/03 are under construction at SSEC and are expected to be delivered to RSMAS in the current fiscal year.

B.1.7 EOS PM-1 Meeting

On May 6, Dr. Otis Brown and Dr. Peter Minnett attended the EOS PM-1 Platform meeting at GSFC. The meeting was called to discuss the need for, and consequences of, a maneuver of the PM-1 satellite to provide the MODIS (and other instruments) on that platform with an opportunity to measure cold space radiances. This maneuver is the same as is required for the AM-1 Platform. From the MODIS standpoint, the need for this maneuver stems directly from the angular effects of the reflectivity of the MODIS scan mirror coating and the inability to characterize this to sufficient accuracy prior to launch.

The outcome of the meeting is that the PM-1 project will explore the feasibility and ramifications of such a maneuver soon after launch. also at later times in the mission.

A summary of parts of the presentation is given in the Appendix.

B.1.8 Wide Area Networking

No changes in current configuration. The current configuration of 20+ workstations is being operated on a 7x24 basis with >300Gb of data exchanged daily. This will provide needed validation prior to shifting of all data processing activities over to ATM.

B.1.9 Documentation

The MODIS Infrared Sea Surface Temperature Algorithm Technical Basis Document (ATBD-MOD-25; available from *http://www.rsmas.miami.edu/modis* in pdf or ps formats) was revised and presented at the ATBD Review on November 20, 1996. No serious criticisms were raised during the ATBD review process. We have not received the written critique from the review panel. However, we look forward to addressing the panel's concerns.

C. Investigator Support

January	W. Baringer		**April**	W. Baringer	A. Mariano
	O. Brown			O. Brown	P. Minnett
	P. Evans			P. Evans	R. Sikorski
	J. Hanafin			G. Goni	J. Splain
	A. Li			K. Kilpatrick	S. Walsh
	D. Wilson-Diaz			A. Li	
February	W. Baringer		**May**	W. Baringer	A. Mariano
	O. Brown			O. Brown	P. Minnett
	P. Evans			P. Evans	R. Sikorski
	R. Sikorski			G. Goni	J. Splain
				A. Li	S. Walsh
March	W. Baringer	P. Minnett	**June**	W. Baringer	A. Li
	O. Brown	R. Sikorski		J. Brown	A. Mariano
	P. Evans			O. Brown	P. Minnett
	G. Goni			P. Evans	R. Sikorski
	A. Li			M. Framiñan	S. Walsh
	A. Mariano			G. Goni	

D. Future Activities

D.1 Current:

D.1.1 Algorithms

a. Continue to develop and test algorithms on global retrievals
b. Evaluation of global data assimilation statistics for SST fields
c. Continue radiative transfer modeling using RAL code
d. Continue analysis of Combined Sensor Cruise, data
e. Continue to study near-surface temperature gradients
f. Continue planning of post-launch validation campaigns.
g. Validation Plan updates (as needed)
h. EOS Science Plan updates (as needed)
i. Define and implement an extended ATM based network test bed
j. Evaluate and analyze results of calibration/validation experiment
k. Continued integration of new workstations into algorithm development environment
l. Continued participation in MODIS Team activities and calibration working group.

D.1.2 Investigator support

Continue current efforts.

D.1.3. CASOTS Workshop

Dr. Peter Minnett has been invited to attend a workshop of the CASOTS Group (Concerted Action for the Study of the Ocean Thermal Skin - a program supported by the European Community) to be held in late October at the Joint Research Centre of the European Community in Ispra, Italy.

E. Problems

No new problems to report.

F. Publications and Presentations

Knuteson, R.O., F.A. Best, H.B. Howell, P. Minnett, H.E. Revercomb, and W.L. Smith. High Spectral Resolution Infrared Observations at the Ocean-Atmosphere Interface in the Tropical Western Pacific using a Marine Atmospheric Emitted Radiance Interferometer (M-AERI): Applications to SST Validation and Atmospheric Spectroscopy. Presented at the Ninth Conference on Atmospheric Radiation, 2-7 February 1997, Long Beach, CA.

Minnett, P.J. and R.O. Knuteson. Measurements of the Thermal skin effect and diurnal thermocline in the tropical Pacific Ocean. Presented at the 7th Science Team Meeting of the Atmospheric Radiation Measurements Program, March 1997, San Antonio, TX.

Post. M.J., C.W. Fairall, A.B. White, Y. Han, W.L. Ecklund, K.M.. Weickmann, D.I. Cooper, P.J. Minnett, P.K. Quinn, S.M. Sekelsky, R.E. McIntosh and R.O. Knuteson, 1997. The Combined Sensor Program: An Air-Sea Science Mission in the Central and Western Pacific Ocean. *Bull. Am. Meteor. Soc*. (Submitted)

Appendix

<u>The need for a space view maneuver</u>

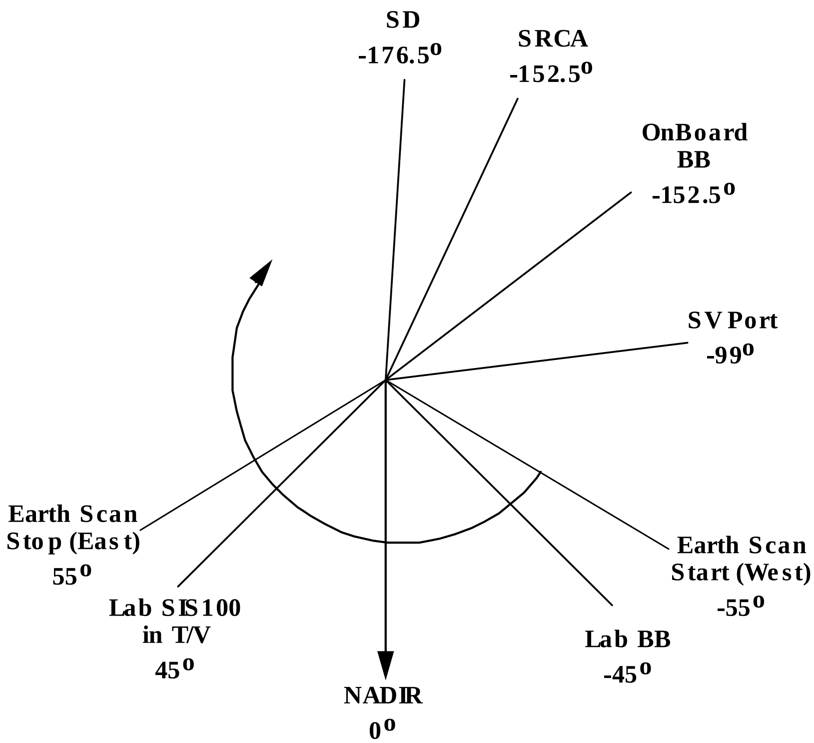
The infrared bands of MODIS form a self-calibrating radiometer in which absolute radiance measurements are determined by a calibration cycle that consists of measurements of an on-board black-body calibration target, the temperature of which is well known, and of cold space. These calibration measurements are made at each rotation of the scan mirror. As the black-body and space view are both external to the optical train of the instrument, this procedure should provide a good radiometric calibration of the Earth-view measurements, and is the same approach as is used on the heritage instrument, AVHRR. A very similar approach is also used on the ATSR (Along-Track Scanning Radiometer) on the ERS-1 and ERS-2 satellites, which is generally acknowledged as being the best calibrated infrared spacecraft radiometer used for SST measurements; the difference being that ATSR uses two internal black-body targets, the temperatures of which are maintained to bracket the signal originating at the sea-surface.

The major, critical difference between MODIS and both AVHRR and ATSR is the scan mirror; differences are of two types: its construction, and its use. For AVHRR and ATSR the scan mirror is such that radiation entering the optical train of the radiometer is incident on the scan mirror at a constant angle, 45^{o} for AVHRR and 23.45^{o} for ATSR. This is constant for the Earth views and the calibration measurements, so any imperfections in the properties of the mirror are compensated through the calibration cycle (provided they are constant over the period of a scan, ~0.17 second).

In the case of MODIS the instrument design is such that the Earth-view measurements are taken over a range of incidence angles of the scan mirror (10.5^{o} to 65^{o}) while the black-body and space-view measurements are taken at angles of 26.3^{o} and 11.4^{o} respectively (see Figure A.1). Thus, to conduct the inflight calibration correctly, the changes in mirror properties with angle of incidence must be known to a level at which the resultant uncertainties do not break the measurement error budget.

Because of the multi-layer coating on each of the two sides of the scan mirror, the angular and polarization properties of the infrared reflectivity are both complex and not well known. Measurements of witness samples of the mirror material and coating by two independent groups have produced inconsistent results, and the discrepancies between these measurements are much greater than the necessary uncertainties required for the MODIS SST retrieval to meet specifications (please see Figure A.2).

A similar problem has been experienced by the GOES-8 and GOES-9 Imagers, which have a comparable mirror coating ("Denton" coating), but which use a much smaller range of incidence angles for the Earth-view scan (from 40^{o} to 50^{o}, *i.e.*, a 10^{o} range compared with 55^{o} for MODIS). The solution adopted to correct for the mirror effects in the GOES radiometer is to make measurements of cold space, in which the measured radiance is dominated by the mirror emission, and devise a correction term based on knowledge of the scan mirror temperature (see Figure A.3) Experience with the GOES instruments shows that such a correction can be made and that the mirror properties are sufficiently stable for the correction not requiring revision with time spans of a year (M. Weinreb, Pers. Comm., 1997).



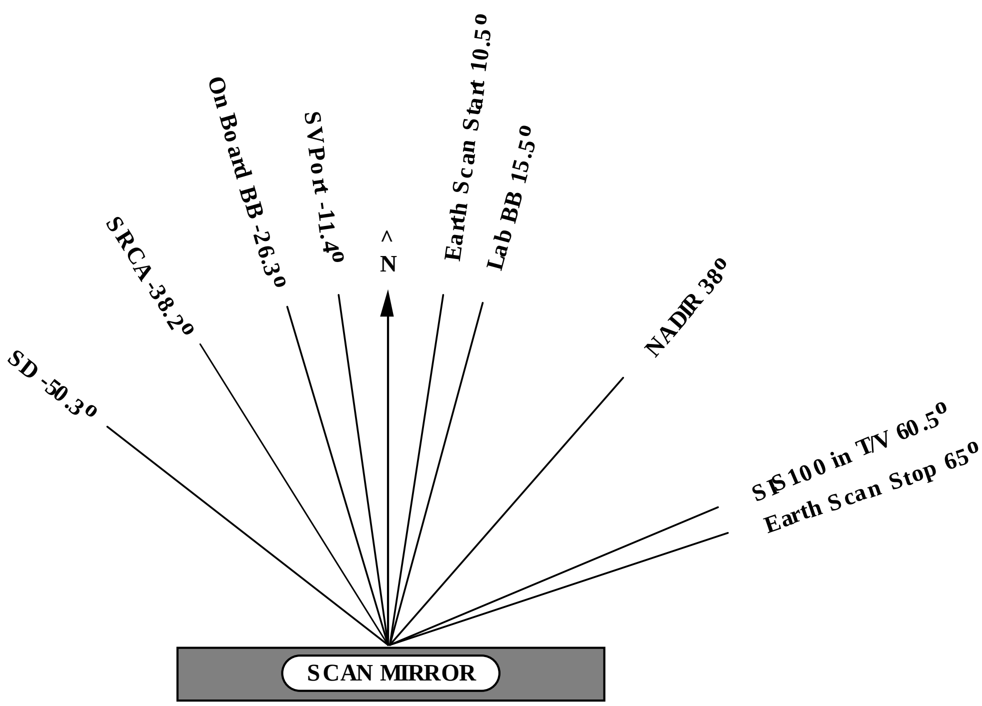
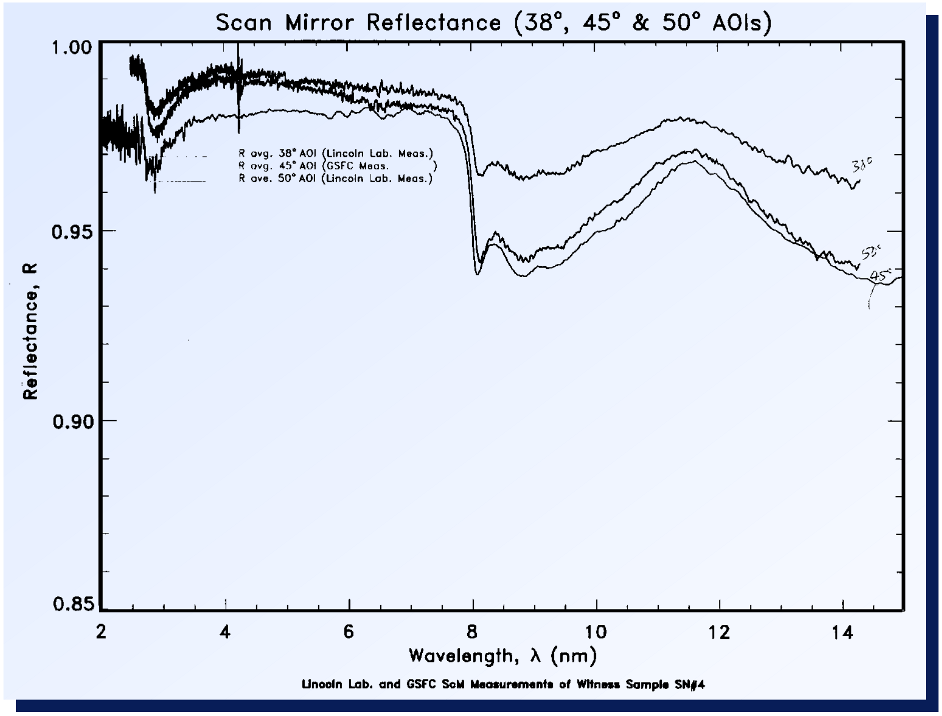


Figure A.1 MODIS mirror positions relative to nadir for various key positions in the scan (above) and the corresponding angles of incidence at the mirror surface (below). Taken from the Draft of the MODIS Level 1b Algorithm Theoretical Basis Document v2.0.



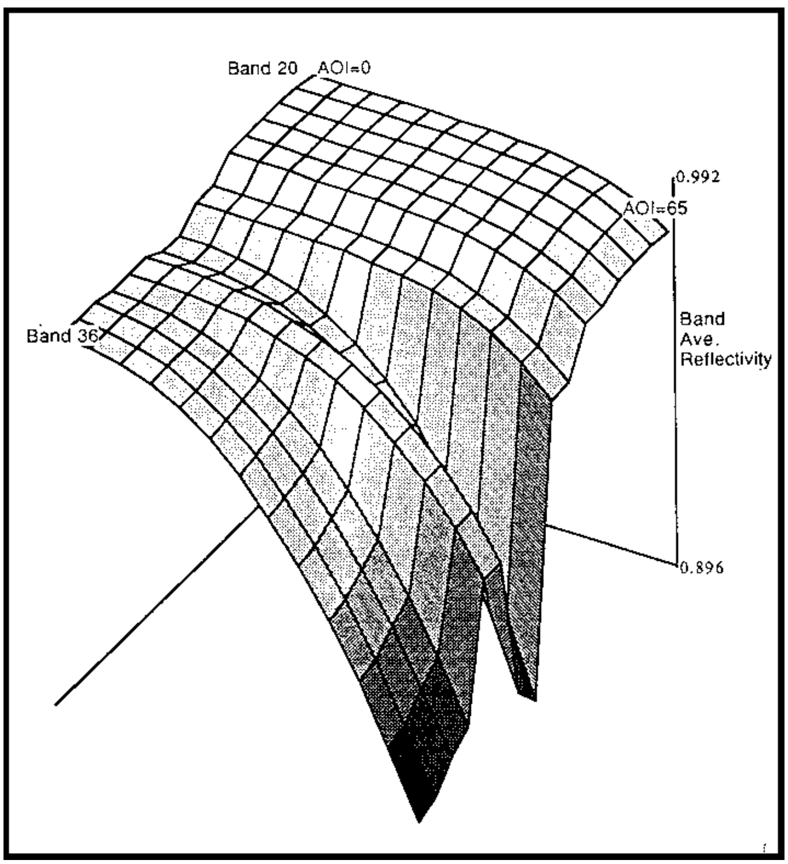


Figure A.2. Measurements of the spectral dependence of the MODIS scan mirror witness sample's reflectivity at three angles of incidence (above), taken at MIT Lincoln Labs (A0I=38° and 50°) and GSFC (A0I=45°). The lower curve is the 45° measurement, and would be expected to lie between the two other curves. The surface fit of the Lincoln Labs data for the infrared bands 20 to 36 (below) shows the most rapid changes in reflectivity occur in the thermal infrared bands.

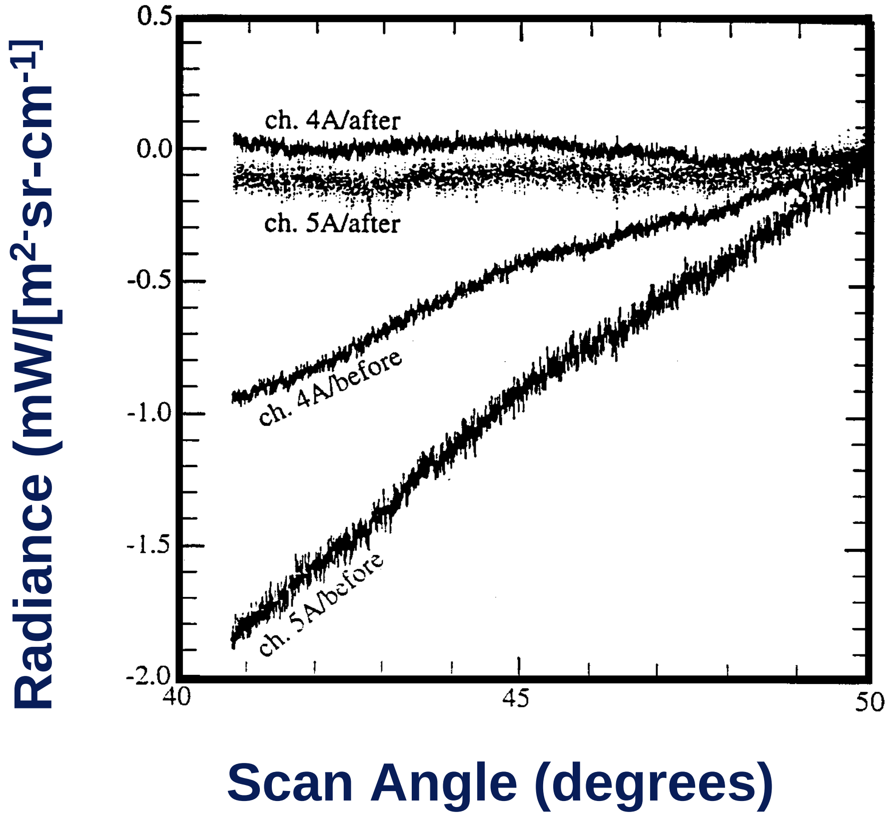


Figure A.3. The GOES scan mirror reflectivity in the thermal infrared channels (corresponding to MODIS bands 31 and 32) before and after correction using the space scan measurements [Weinreb et al., 1996]. The range of angles of incidence on the scan mirror is 10^{o}.

The GOES space scan can be accomplished with relatively little perturbation to the routine operational sequence, and therefore is done frequently, every few weeks, whereas, the EOS AM-1 space scan requires a major perturbation to the spacecraft pointing. Nevertheless, it can be done while the spacecraft is in the Earth eclipse portion of a single orbit resulting in loss of Earth scan data over a period of <40 minutes.

The benefits of this maneuver to the MODIS infrared scientific data are great. With the maneuver and the deep space scan data, the Earth-view measurements can be corrected for the angular effects of the scan mirror to a sufficient degree to bring the derived SST measurements close to the design specification. Without the maneuver the specifications cannot be met.

Atmospheric Correction Algorithm

The MODIS SST atmospheric correction algorithm will follow the form of that used with great success on the heritage instrument, AVHRR, which is called the Non-Linear SST algorithm:

$$SST = a_o + a_1 + T_{31} + a_2\left(T_{31} - T_{32}\right)f(T) + a_3\left(T_{31} - T_{32}\right)\left(\sec\theta - 1\right)$$

where T_{31}, T_{32} are the brightness temperatures measured at the top of the atmosphere in MODIS bands 31 and 32, a_i are numerical coefficients and $f(T)$ is a function of a "first guess" surface temperature. (In the current NLSST, this is simply a "climatological" temperature).

The information about the atmospheric effect is mostly provided by the difference in the brightness temperatures at wavelengths ~11μm and ~12μm (MODIS channels 31 and 32), which results primarily from differential absorption by atmospheric water vapor.

The success of the correction relies on the channel brightness temperature differences being accurately measured. These differences range from <0.2K to ~4K in going from polar to tropical atmospheres. The satellite zenith angle term in the NLSST accounts for the changing path length effects for slanting propagation paths through the atmosphere for measurements away from nadir. In dry atmospheres the changes in sea-surface emissivity with emission angle also contribute to the scan angle effects in the top of atmosphere radiance measurements.

The NLSST can be approximated by the "canonical" MCSST (Multichannel Sea Surface Temperature) algorithm for retrievals at nadir:

The typical NLSST algorithm (using coefficients for the AVHRR on NOAA-14) is:

$$NLSST = 0.9465T_{31} + 0.084T_s(T_{31} - T_{32}) + 0.751(T_{31} - T_{32})(\sec\theta - 1) - 257.2$$

At nadir *sec*θ*=1*

For T_s=23.8°C

$$NLSST' = 0.9465T_{31} + 2.0(T_{31} - T_{32}) + a_o$$
$$\cong 3T_{31} - 2T_{32} + a_o$$

This simple expression can be used to estimate the propagation of errors through the atmospheric correction.

<u>Error budget given desired uncertainty in SST retrieval</u>

The stated objective is to determine SST with an RMS uncertainty of 0.33K (1σ).

There are three classes of contributions to the error budget for skin SST retrieval: errors caused by uncertainty in the surface emissivity; errors caused by uncertainties in the atmospheric correction; and errors caused by instrumental effects. These are uncorrelated and so contribute in a "root-sum-square" sense.

Errors caused by surface emissivity uncertainties

The sea surface emissivity can be measured using the M-AERI (Smith *et al*.., 1996) and the angular dependency appears to be in good agreement with earlier modeling results (*e.g.,* Masuda *et al*.., 1988). The effects of wind speed on the areal averaged value of emissivity, resulting from the ensemble of tilted surface facets in a roughened sea, have long been thought of as being a significant source of error in infrared SST measurement. However, recent modeling results of sea surface emission that include the effects of multiple reflection at a rough surface (Watts *et al.*, 1995) show that the wind speed effect on emissivity is very small and the effects on derived SST are <0.1K, say 0.05K.

Errors caused by uncertainties in the atmospheric correction

Published studies of the residual errors in atmospheric correction algorithms range from 0.05 to 0.4K, (Minnett, 1986, Barton *et al*., 1989, Závody *et al*., 1995). These are caused by the natural variability of the temperature and humidity distributions in the atmosphere, and result in variability in the atmospheric transmission, upwards emission into the beam measured by the satellite radiometer and downward atmospheric emission reflected into the beam at the sea surface. The smaller values are associated with algorithms optimized for smaller ranges of seasonal or regional conditions.

Assuming that the MODIS algorithms will be reasonably well optimized for regional and seasonal atmospheric variability building on the NOAA/NASA AVHRR Pathfinder results and earlier numerical simulations, (*e.g.*, Minnett, 1990), the residual SST uncertainty caused by the atmospheric correction algorithm is ~0.2K.

Instrumental uncertainties

Given the target SST accuracy and the non-instrumental sources of SST uncertainties, the errors introduced in the SST measurements by instrumental effects must be <0.26K.

In the canonical atmospheric correction algorithm, for errors that are uncorrelated between each band:

$$\varepsilon(SST) \approx \left(9(\varepsilon T_{31})^2 + 4(\varepsilon T_{32})^2\right)^{1/2}$$

And if

$$\varepsilon(T_{31}) \cong \varepsilon(T_{32})$$

$$\varepsilon(SST) = \sqrt{13}(\varepsilon T_{31})$$

For $\varepsilon(SST) =$ 0.33K, this implies $\varepsilon T_{31} \cong \varepsilon T_{32} \cong 0.07K$

If the errors are totally correlated between the two bands, the algorithm does not greatly magnify them, and acceptable $\varepsilon(T_{31})$ and $\varepsilon(T_{32})$ would be ~0.26K.

This implies a requirement of the instrument to provide top of atmosphere radiance measurements at the 0.1 to 0.35% level.

Instrument Performance

Analysis of instrument performance by Dr. G. Godden (Fax message, dated May 2, 1997) shows that before the spacecraft maneuver to view deep space, the radiometric uncertainties in Bands 31 and 32 are at the 0.9 to 1.0% level, and at the 0.2 to 0.25% level after the maneuver; Band 32 being lower than Band 31.

For a target at 300°K, a 0.1°K uncertainty in brightness temperature results from a 0.15% radiometric uncertainty in Band 31* and 0.13(5)% in Band 32. At 278°K, these values are 0.17% and 0.16%.

Thus, before the deep space view, the brightness temperature uncertainties are expected to be in the range of 0.56°K (278°K target) to 0.67°K (300°K target). Propagating these through the atmospheric correction algorithm at nadir results in SST errors from this contribution of 2.3°K (278°K target) to 2.4°K (300°K target) for uncorrelated errors, and 0.6 to 0.7°K for correlated errors.

Including the contributions from emissivity and atmospheric variability does not significantly increase the resultant SST uncertainties, for uncorrelated errors, but increases them by about 0.03°K for correlated errors.

After a maneuver to view deep space, the brightness temperature uncertainties are expected to be in the range of 0.12°K to 0.16°K for Band 31 (300°K and 278°K) and 0.17°K to 0.18°K for Band 32.

These contribute uncertainties in the SST measurement of ~0.56°K to 0.63°K, if uncorrelated. When the contributions from surface emissivity and atmospheric variability are included, the SST uncertainties become 0.59°K at 300°K and 0.66°K at 278°K. If the instrumental uncertainties are correlated these values are 0.34°K and 0.30°K.

The error budgets before and after maneuver are summarized in Tables 1 and 2.

The errors in the brightness temperatures in Bands 31 and 32 are likely to be correlated to some degree and therefore the worst uncertainties in SST before the maneuver are not expected to be experienced. However, it is very unlikely they will be totally correlated, so the smaller figures are also not expected to be found. Also, if the errors are dominated by correlated components, they cannot be reduced by spatial averaging, as is the case for errors that are uncorrelated pixel to pixel.

Other Considerations

Timing of the space view maneuver is also of concern. An early successful characterization of the mirror provides a basis for post-launch calibration/validation efforts, delivery of SST products which meet the MODIS accuracy requirements and minimizes potential reprocessing of

* Using center wavelengths of 11.03µm for Band 31 and 12.02µm for Band 32.

data taken prior to implementation of an improved characterization.

Reprocessing
A major issue would be added processing load to recoup all the data collected before the instrument is appropriately characterized. Consider: the errors prior to adequate characterization will render the SST data virtually unusable, certainly of a quality much less than NOAA/AVHRR or ERS/ATSR observations. Calibration/validation of such data would not be a good investment of resources. ON the other hand, one could potentially save processing cycles prior to characterization by not producing L2 and L3 SST products, i.e., only produce L1A/B products.

Data quality
Indications from the GOES 8/9 experience are that the Denton mirror coatings are temporally stable. There has not been any degradation noted after more than a year. However, there are two caveats to this result: 1) MODIS has a higher level of digitization [more digital bits], and 2) the scan angle for MODIS is larger by a factor of 5. That is, MODIS IR observations could be inherently more sensitive to temporal degradation than GOES.

Given that there is not any observed temporal degradation in the MODIS mirror emissivity, the reprocessed data should be as good as the data after the maneuver was done. The time that the characterization is accomplished sets a time interval for high-quality SST fields, valid calibration/validation activities, and so on.

Early Science
Early science with the thermal bands will be strongly impacted by the timing of the spacecraft maneuver. There will be no data available for such science until the characterization is completed. Data products prior to such a characterization will not be a credit to the project, the instrument, or the investigators.

Summary

The target uncertainty in the SST cannot be met even after the spacecraft maneuver on a pixel-by-pixel basis unless the uncertainties in the brightness temperatures are well correlated or unless the residual contribution due to atmospheric variability can be reduced below $\sim 0.2^{o}$K in each channel. This latter opinion is the subject of continuing study. If this cannot be achieved the residual SST uncertainties in individual pixels will be about a factor of two greater than the required accuracy. This is comparable to published estimates of the residual uncertainties in present-day AVHRR SST measurements. Reduction of the MODIS uncertainties can be expected to result from pixel averaging.

Prior to the spacecraft maneuver, the RMS uncertainties in the SST measurements may be >2K, which is unacceptable for any of the EOS scientific applications. Even in the most optimistic case (correlated brightness temperature errors) the SST uncertainty is greater than requirements and cannot be reduced by pixel averaging.

This error analysis is approximate in that it does not follow the true characteristics of the NLSST algorithm, nor the interplay between uncertainties caused by atmospheric variability and surface emissivity as the atmospheric transmission changes.

Errors in the NLSST will generally increase away from nadir as the ($sec\theta$-1) term grows and decrease towards the poles as the T_s term decreases. As the atmosphere becomes drier the transmissivity increases and the errors caused by uncertainties in the emissivity increase; in moist, tropical atmospheres these become very small.

This discussion serves to show that without the notable improvement in brightness temperature accuracies resulting from the spacecraft deep space maneuver, the uncertainties in the SST retrievals are unacceptable for scientific applications.

MODIS products which use thermal bands are heavily impacted by the need for on-orbit characterization of the scan mirror. Post launch reprocessing of pre-maneuver datasets is also an additional load on the EOS core system. Calibration/validation activities are not applicable to the data stream until the characterization is complete. Early science results could be severely limited by the timing of the on-orbit maneuver. From the standpoint of the MODIS IR investigators, it is better to do the maneuver earlier in the mission than later.

Table 1

SST Error Budget BEFORE maneuver

Source of Uncertainty	Target T=278^oK	Target T=300^oK
T_{31} brightness temperature	0.59	0.67
T_{32} brightness temperature	0.56	0.67
Atmospheric correction	2.32 (0.65)	2.42 (0.67
Atmospheric variability	0.2	0.2
Surface emissivity	0.05	0.05
TOTAL	**2.33 (0.68)**	**2.42 (0.70)**

Table 2

SST Error Budget AFTER maneuver

Source of Uncertainty	Target $T=278^oK$	Target $T=300^oK$
T_{31} brightness temperature	0.18	0.17
T_{32} brightness temperature	0.16	0.12
Atmospheric correction	0.63 (0.22)	0.56 (0.27)
Atmospheric variability	0.2	0.2
Surface emissivity	0.05	0.05
TOTAL	**0.66 (0.30)**	**0.59 (0.34)**

Numbers in parentheses are for correlated errors in Bands 31 and 32. All values in Kelvin.

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